

BACKGROUND OF THE INVENTION

5 The present invention relates to a vibration
wave driving apparatus which obtains driving force
from vibration waves such as ultrasonic waves.

A vibration wave driving apparatus which obtains driving force in three degrees of freedom (3D direction) by using vibration waves such as ultrasonic waves has been proposed. Japanese Patent Application Laid-Open No. 11-220891 discloses a vibration wave driving apparatus which can excite, in a Langevin type vibration element, in-plane expansion and contraction vibrations that displace in a longitudinal direction and two different types of output-of-plane bending vibrations that displace in a direction perpendicular to the longitudinal direction. When at least two of these three types of vibrations are excited and synthesized, the driven member can be translated or rotated in an arbitrary direction.

Although vibration wave driving apparatuses are required to be reduced in size and improved in function, the vibration wave driving apparatus disclosed in Japanese Patent Application Laid-Open No. 11-220891 are subjected to constraints in terms of a

reduction in size in the longitudinal direction because in-plane expansion and contraction vibrations that displace in the longitudinal direction of the vibration element must be generated. As the size in
5 the longitudinal direction decreases, the frequency of in-plane expansion and contraction vibrations increases. For this reason, to decrease this frequency to a practical frequency, a certain size must be ensured in the longitudinal direction.

10 A vibration wave driving apparatus whose size in the longitudinal direction is reduced is disclosed in US Patent No. 5,917,268. This apparatus is designed to generate driving force in two degrees of freedom by exciting two types of in-plane expansion
15 and contraction motions and natural modes of two types of out-of-plane bending vibrations in a planar type vibration element. More specifically, the driven member is translated or driven in the first direction by synthesizing a first in-plane expansion
20 and contraction motion and third out-of-plane bending vibration. The driven member is translated or driven in the second direction by synthesizing second in-plane expansion and contraction motion and fourth out-of-plane vibration.

25 This vibration wave driving apparatus is, however, designed to generate driving force in two degrees of freedom, but there is no suggestion about

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SUMMARY OF THE INVENTION

According to one aspect of this invention,
15 there is provided a vibration wave driving apparatus
which drives a driven member by the vibrations
excited in a vibration member having electro-
mechanical energy conversion elements, wherein the
vibration member has a shape line symmetrical with
20 respect to two planes orthogonal to each other, and
the electro-mechanical energy conversion elements can
excite three different types of bending vibrations,
in the vibration member, which displace in a
direction of axis common to two planes.

25 This vibration wave driving apparatus can drive
the driven member in an arbitrary direction in three
dimensions by selectively exciting two of the three

types of bending vibrations.

Since three types of bending vibrations that displace in the same direction are excited, the vibration member may have a plate-like shape and can be formed thin. In addition, since all the vibrations excited by the electro-mechanical energy conversion elements are bending vibrations, the natural vibration frequency can be suppressed low as compared with expansion and contraction vibrations. This makes it possible to reduce the size of the vibration wave driving apparatus.

Note that two of the three different types of bending vibrations have the same vibration pattern and are 90° out of phase in the same plane.

The electro-mechanical energy conversion elements capable of exciting the three types of bending vibrations are preferably arranged in the same plane.

Other features and advantages of the present invention will be apparent from the following description taken in conjunction with the accompanying drawings, in which like reference characters designate the same or similar parts throughout the figures thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are

5 Fig. 1 is a perspective view showing a
vibration element according to an embodiment of the
present invention;

Fig. 3 is a view showing the arrangement of the piezoelectric elements of the vibration element in Fig. 1 and a connected state;

Fig. 5 is a view showing a vibration wave driving apparatus using the vibration element in Fig. 1 and a spherical driven member;

Figs. 7A, 7B and 7C are views showing a
25 modification of the vibration element in Fig. 1;

Figs. 8A and 8B are views showing another modification of the vibration element in Fig. 1;

Fig. 9 is a schematic view showing other natural vibration modes that can be excited in the vibration element in Fig. 1;

Fig. 10 is a perspective view showing a vibration element according to another embodiment of the present invention;

Fig. 11 is a schematic view showing the natural vibration modes excited by the vibration element in Fig. 10; and

Fig. 12 is a view showing the arrangement of the piezoelectric elements of the vibration element in Fig. 10 and a connected state.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 is a perspective view of a vibration element 1 according to an embodiment of the present invention. Fig. 2 is a schematic view showing the natural vibration modes excited by the vibration element 1 according to this embodiment. The arrows in Fig. 2 indicate the relative positional displacements of the respective natural modes.

The vibration element 1 is comprised of a vibration member 2 shaped such that a plurality of projections are formed on surface of a substantially square plate made of a metal such as phosphor bronze and piezoelectric elements 3 which are bonded and fixed to the vibration member 2 and serve as electro-

mechanical energy conversion elements. Contact
projections PC1 to PC4 (to be described later) are
formed at four substantially middle positions on the
outer sides of the vibration element 1. The contact
5 projections PC1 to PC4 protrude in the Z-axis
direction to come into contact with a driven member
(not shown) so as to transfer driving force to the
driven member. These contact projections PC1 to PC4
respectively have driving points C1 to C4, on their
10 end faces, which serve to transfer driving force to
the driven member. Wear-resistant members which are
made of SUS or the like and have undergone a surface
oxidation process are integrally attached to the
driving points C1 to C4 with an adhesive or the like.
15 Projections PE1 to PE4 are formed at four
substantially corner positions of the vibration
element 1. A projection PG is formed on a
substantially central portion of the vibration
element 1. A pressurizing magnet 5 for attracting or
20 pressurizing the driven member (not shown) is placed
on the central portion of the vibration member 2.

Assume that two axes which are parallel to
substantially the square-plate-like surface of the
vibration element 1 and perpendicular to each other
25 are the X- and Y-axes, and an axis which is
perpendicular to both the X- and Y-axes is the Z-axis.
The vibration element 1 is formed to have a line

symmetrical shape with respect to the X-Z plane and Y-Z plane as central.

In this embodiment, as shown in Fig. 2, vibration modes Mode _{α} , Mode _{β x}, and Mode _{β y} are natural vibration modes that cause out-of-plane deformation in the X-Y plane (vibration displacements in the Z-axis direction) of the vibration element 1. Of Mode _{α} , Mode _{β x}, and Mode _{β y}, Mode _{β x} and Mode _{β y} having the same waveform pattern are referred to as equal-root mode vibrations. Mode _{β x} and Mode _{β y} have the same waveform pattern and are overlaid on each other in the X-Y plane with a phase shift of 90°.

Mode _{β x} in Fig. 2 has three antinodes (two nodes) in the Y-axis direction and two antinodes (one node) in the X-axis direction. When Mode _{β x} and Mode _{β y} with a phase shift of 90° are overlaid on each other, nodes of Mode _{β x} overlay antinodes of Mode _{β y} at some positions, and antinodes of Mode _{β x} overlay nodes of Mode _{β y} at some positions. The contact projections PC1 to PC4 are formed at these positions.

Assume that driving currents having the same waveform are applied to the piezoelectric elements 3 respectively corresponding to the Mode _{β x} and Mode _{β y} to excite Mode _{β x} and Mode _{β y}. Even in this case, if the shape of the vibration element 1 itself is not uniform, the vibration patterns are affected by the

shape of the vibration element 1 to result in an offset.

The vibration element 1 is therefore preferably formed to be line symmetrical with respect to the X-Z plane and Y-Z plane which are perpendicular to each other to prevent an offset between the respective vibration patterns due to the shape of the vibration element 1 when driving currents are applied to the piezoelectric elements 3 to generate vibrations in the same pattern.

In Mode $_{\beta x}$ and Mode $_{\beta y}$ in Fig. 2, the piezoelectric elements for exciting vibrations in the same vibration pattern are arranged with a phase shift of 90° . If the shape of the vibration element 1 is line symmetrical with respect to the X-Z plane and Y-Z plane as central and equal in size in the X-axis direction and Y-axis direction, the resultant natural vibration frequencies coincide with each other. Note that in this embodiment, Mode $_{\beta x}$ and Mode $_{\beta y}$ are excited by the common piezoelectric elements.

Mode $_{\alpha}$ in Fig. 2 is common to Mode $_{\beta x}$ and Mode $_{\beta y}$ in terms of out-of-plane vibrations but differs from them in their vibration patterns. In most cases, therefore, the natural vibration frequency of Mode $_{\alpha}$ differs from that of Mode $_{\beta x}$ and Mode $_{\beta y}$. It is therefore necessary to match the

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natural vibration frequency of Mode $_{\alpha}$ with that of
Mode $_{\beta x}$ and Mode $_{\beta y}$. As is obvious from Fig. 2, in
this embodiment, out-of-plane vibrations in Mode $_{\beta x}$
and Mode $_{\beta y}$ are shorter in wavelength than those in
5 Mode $_{\alpha}$, and hence the natural vibration frequency of
Mode $_{\beta x}$ and Mode $_{\beta y}$ is higher than that of Mode $_{\alpha}$.
For this reason, the projections PE1 to PE4 are
formed at the four substantially corner positions
where the vibration amplitude of Mode $_{\beta x}$ and Mode $_{\beta y}$
10 is relatively large to increase the mass, thereby
suppressing the natural vibration frequency of
Mode $_{\beta x}$ and Mode $_{\beta y}$ and matching it with the natural
vibration frequency of Mode $_{\alpha}$. By forming these
projections PE1 to PE4, the vibration displacements
15 of the driving points C1 to C4 can be increased.

Fig. 3 shows the arrangement of piezoelectric
elements 3-1 to 3-8 which are arranged on the back
surface of the vibration member 2 to excite natural
vibration modes Mode $_{\alpha}$, Mode $_{\beta x}$, and Mode $_{\beta y}$ in the
20 vibration element 1. In the vibration element 1
shown in Fig. 1, the piezoelectric elements 3-1 to 3-
8 are arranged in the same plane without overlapping.

Referring to Fig. 3, (+) and (-) indicate the
polarization directions of the respective
25 piezoelectric elements 3. Terminals A, B, and C and
the lines connecting them to the respective
piezoelectric elements 3 schematically show

application terminals for driving vibrations and a connected state. "G" connected to the vibration member 2 indicates a common potential. When an alternating signal is applied to the terminal A, Mode_α is excited. When alternating signals with opposite phases are applied to the terminals B and C, Mode_{βx} is excited. When alternating signals in phase are applied to the terminals B and C, Mode_{βy} is excited. Mode_{βx} and Mode_{βy} which are equal-root-mode vibrations are excited on the common piezoelectric elements.

Figs. 4A to 4C show vibration displacement states at the driving points C1 to C4.

Fig. 4A shows a vibration displacement state in which a rotation motion about the Y-axis (R_y in Fig. 1) or a translational motion in the X-axis direction is produced as a relative motion of the vibration element 1 and driven member. Driving signals are applied such that phase of Mode_{βx} is delayed from that of Mode_α as base phase by $\pi/2$. The vibration displacements at the respective driving points C1 to C4 repeat temporal changes as indicated by "t1 → t2 → t3 → t4 → t1" to produce a circular or elliptic motion in the X-Y plane. With this circular or elliptic motion, a relative motion of the driven member, which is brought into contact with the driving points C1 to C4 with pressure, and the

vibration element 1 can be produced. When the vibration element 1 is viewed in the Y-axis direction from the driving point C4 side in Fig. 1, all the driving points C1 to C4 are rotating counterclockwise, with the points C1 and C3 undergoing the same rotational motion and the points C2 and C4 undergoing the same rotational motion. The rotation of the points C1 and C3 is $\lambda/2$ out of phase from the rotation of the points C2 and C4. The points C1 and C3 and the points C2 and C4 alternately come into contact with the driven member. Obviously, when driving signals are applied such that phase of Mode $_{\beta x}$ temporarily goes ahead of that of Mode $_{\alpha}$ as base phase by $\pi/2$, the driving points rotate clockwise.

If, for example, a spherical driven member 4S is selected as shown in Fig. 5, and the vibration element 1 is fixed and supported, the driven member 4S rotates about the Y-axis (R_y). If a flat plate like driven member 4P is selected as shown in Fig. 6A, and the vibration element 1 is fixed and supported, the driven member 4P translates in the X-axis direction.

Fig. 4B shows a vibration displacement state in which a rotational motion about the X-axis (R_x) or a translational motion in the Y-axis direction is produced as a relative motion of the vibration

element 1 and driven member. Driving signals are applied such that phase of Mode_{βy} is delayed from that of Mode_α as base phase by $\pi/2$. As in the case of Mode_α and Mode_{βx}, elliptic motions are produced at the driving points C1 to C4 in the Y-Z plane. When the vibration element 1 is viewed in the X-axis direction from the driving point C1 side in Fig. 1, all the driving points C1 to C4 are rotating counterclockwise, with the points C1 and C3 undergoing the same rotational motion and the points C2 and C4 undergoing the same rotational motion. The rotation of the points C1 and C3 is $\lambda/2$ out of phase from the rotation of the points C2 and C4. The points C1 and C3 and the points C2 and C4 alternately come into contact with the driven member.

If the spherical driven member 4S is selected as shown in Fig. 5, and the vibration element 1 is fixed and supported, the driven member 4S rotates about the X-axis (Rx). If the flat driven member 4P is selected as shown in Fig. 6A, and the vibration element 1 is fixed and supported, the driven member 4P translates in the Y-axis direction.

Fig. 4C shows a vibration displacement state in which a rotational motion about the Z-axis (Rz) is produced as a relative motion of the vibration element 1 and driven member. Driving signals are applied such that phase of Mode_{βy} is delayed from

that of Mode_{βx} as base phase by $\pi/2$. Elliptic motions are produced at the driving points C1 to C4 in the X-Y plane. Figs. 4A and 4B show the vibration displacements at the respective driving points in the same plane. In contrast to this, Fig. 4C shows the vibration displacements at the driving points C1 and C3 in the Y-Z plane, and the vibration displacements at the driving points C2 and C4 in the X-Z plane. When the vibration element 1 is viewed in the X-axis direction from the driving point C1 side in Fig. 1, the driving point C1 is rotating clockwise. When the vibration element 1 is viewed in the Y-axis direction from the driving point C2 side, the driving point C2 is rotating clockwise. When the vibration element 1 is viewed in the X-axis direction from the driving point C3 side, the driving point C3 is rotating clockwise. When the vibration element 1 is viewed in the Y-axis direction from the driving point C4 side, the driving point C4 is rotating clockwise. Since the rotational motions of the driving points C1 to C4 are $\lambda/4$ out of phase from each other, the driven member sequentially comes into contact with the driving points C1 to C4.

If therefore the spherical driven member 4S is selected as shown in Fig. 5, and the vibration element 1 is fixed and supported, the driven member 4S rotates about the Z-axis (R_z). If the flat driven

member 4P is selected as shown in Fig. 6A, and the vibration element 1 is fixed and supported, a relative rotational motion about the Z-axis (R_z) can be produced between the driven member 4P and the vibration element 1.

Although the motions in the respective axial directions and about the respective axes have been separately described above, driving forces can be generated in arbitrary directions by combining the respective natural vibration modes. When an elliptic driven member 4E is selected as shown in Fig. 6B and the vibration element 1 is fixed and supported, driving forces can be generated in the driven member to rotate it about the X-axis (R_x) and Y-axis (R_y) or a combination of these forces can be produced to move it in an arbitrary direction. If a driven member having a curved surface is used, the member can be driven about an arbitrary axis.

The spherical driven member 4S in Fig. 5 is a CCD camera. That is, Fig. 5 shows an example of how the vibration wave driving apparatus according to this embodiment is applied to a positioning mechanism for the CCD camera. A CCD camera E is incorporated in the spherical driven member 4S. The CCD camera E can be positioned in an arbitrary direction by the driving force generated by the vibration element 1.

Figs. 7A to 7C show another arrangement of a

vibration element 11 according to this embodiment.
Fig. 7A is a plan view. Fig. 7B is a sectional view
taken along a line 7B-7B in Fig. 7A. Fig. 7C is a
sectional view taken along a line 7C-7C in Fig. 7A.

5 A vibration member 12 as a part of the
vibration element 11 is formed by pressing using an
iron-based plate member. The vibration element 11 is
comprised of the vibration member 12 and
piezoelectric elements 13 as in the case of the
10 vibration element 1 in Fig. 1. The forms of natural
vibration modes excited in the vibration element 11
are also the same as those in Fig. 2. Contact
projections PC11 to PC14 have driving points C11 to
C14 at their distal ends. The contact projections
15 PC11 to PC14 protrude in the Z-axis direction and
also protrude outward in the X-Y plane. This
arrangement makes it possible to enhance the
displacements of the driving points C11 to C14.
Likewise, projections PE11 to PE14 protrude in the Z-
20 axis direction and also protrude outward in the X-Y
plane and serve to increase the mass at four
substantially corner positions where the vibration
amplitudes of Mode _{β x} and Mode _{β y} are relatively
large, thereby matching the natural vibration
25 frequencies of Mode _{α} , Mode _{β x}, and Mode _{β y} with each
other.

The shape of the vibration element 1 is not

limited to this. As other shapes that obtain the effects of the present invention, for example, the shapes of vibration elements 21 and 31 shown in Figs. 8A and 8B may be used. The natural vibration modes
5 excited by the vibration element 21 are not limited to the above modes. For example, the same driving operation as that described above can be performed by using the natural vibration modes shown in Fig. 9.

Fig. 10 is a perspective view showing a
10 vibration element 41 according to another embodiment of the present invention. Fig. 11 is a schematic view showing the natural vibration modes excited by the vibration element 41. The arrows in Fig. 11 indicate the relative displacements of the respective
15 natural vibration modes.

This vibration element differs from the one shown in Fig. 1 in that contact projections PC41 to PC44 are formed at four substantially corner positions of the vibration element 41, and
20 projections PE41 to PE44 are formed at substantially middle positions on the outer sides of the vibration element 41. In this embodiment, since natural vibration modes having vibrations with the patterns shown in Fig. 11 are generated, the vibration element
25 is formed into a shape that can efficiently excite these natural vibration modes. More specifically, the vibration element 41 is formed to be line

symmetrical with respect to the X-Z plane and Y-Z plane as central. In order to suppress the natural frequency of Mode_ β x and Mode_ β y so as to match it with the natural frequency of Mode_ α , the projections
5 PE41 to PE44 are formed at the four substantially middle positions on the outer sides where the vibration amplitude of Mode_ β x and Mode_ β y is relatively large so as to increase the mass.

Fig. 12 shows the arrangement of piezoelectric
10 elements 43-1 to 43-8 which are arranged on the back surface of a vibration member 42 to excite the natural vibration modes Mode_ α , Mode_ β x, and Mode_ β y in the vibration element 41.

Referring to Fig. 12, (+) and (-) indicate the
15 polarization directions of the respective piezoelectric elements 43. Terminals A, B, and C and the lines connecting them and the respective piezoelectric elements 43 schematically show application terminals for driving vibrations and a
20 connected state. "G" connected to the vibration member 42 indicates a common potential. When an alternating signal is applied to the terminal A, vibration having Mode_ α is excited. When alternating signals with opposite phases are applied to the
25 terminals B and C, vibration having Mode_ β x is excited. When alternating signals in phase are applied to the terminals B and C, vibration having

Mode_{βy} is excited. In this embodiment as well,
Mode_{βx} and Mode_{βy} which are equal-root-mode
vibrations are excited by the common piezoelectric
elements. Other arrangements are the same as those
5 of the vibration element in Fig. 1.

The vibration element shown in Fig. 10 differs
from the one shown in Fig. 1 only in the vibration
patterns of natural vibration modes, but is based on
the same driving principle.

10 When driving signals are applied such that
phase of Mode_{βx} is delayed from that of Mode_α as
base phase by $\pi/2$, a rotational motion about Y-axis
(R_y) or a translational motion in the X-axis
direction is produced as a relative motion of the
15 vibration element 1 and driven member. When driving
signals are applied such that phase of Mode_{βy} is
delayed from that of Mode_α as base phase by $\pi/2$, a
rotation about the X-axis (R_x) or a translational
motion in the Y-axis direction is produced as a
20 relative motion of the vibration element 1 and driven
member. When driving signals are applied such that
phase of Mode_{βy} is delayed from that of Mode_{βx} as
base phase by $\pi/2$, a rotational motion about the Z-
axis (R_z) is produced as a relative motion of the
25 vibration element 1 and driven member.